

On Quasi-Biennial Oscillation in Air-Sea System

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ABSTRACT

From the COADS (Comprehensive Ocean-Atmosphere Data Set) I and the COADS II, we got a monthly data set of sea surface temperature (SST), zonal and meridional wind components at sea level (U,V) and sea level pressure (SLP) with $4^{\circ} \times 4^{\circ}$ grid system covering the period from Jan. 1950 to Dec. 1987 to study the evolutionary features of the quasi-biennial oscillation (QBO) in the air-sea system. The analytic method of complex empirical orthogonal function (CEOF) is used to obtain the composite temporal sequences of amplitude (six phases for half a period) for the first and the second main components of SST, U, V and SLP. It is shown from the results that the main characteristics for different phases of the sea surface temperature anomaly's (SSTA) QBO are warm water / cold water in the equator of the eastern Pacific (EEP). There are two warm or cold water centers of the SSTA in the EEP, which are located in the equator of the central Pacific (ECP) and the east part of the EEP. The features of the source propagation and the influence of these two centers on atmospheric circulation are discussed and it can be seen that in the formation of these two centers, there are different features in oceanic and atmospheric circulations and air-sea coupled process.

1. INTRODUCTION

Quasi-biennial oscillation (hereafter referred to as QBO) was first found in the stratosphere. Reed et al. (1961) revealed the quasi-biennial variation in the stratospheric zonal wind which propagates downward from upper level to about 100 hPa. In 1960's, scientists have not confirmed whether the QBO exists in the troposphere. In recent years, Yasunari (1985) found the QBO from monthly mean zonal wind in the middle and high troposphere and pointed out that not only the QBO but also the quasi three and a half year oscillation exist in the zonal wind at 200hPa. These two oscillations propagate eastward over the equator. In the process of the propagation, that these two oscillations are overlapped in the same phase over the EEP, just happened in the El Nino years. It shows that the occurrence of El Nino relates to the activities of the QBO and other interannual oscillations in the atmosphere; meanwhile, the QBOs were discovered in air temperature over North America (Rasmusson, 1981) in rainfall over China (Huang Jiayou, 1988) and in SLP over the Northern Hemisphere (Trenberth, 1984), respectively. One of the authors of this paper analyzed the data, covering the period from 1950 to 1979, of COADS I, and showed the existence of the QBO and the quasi three and a half year oscillation in SST, U, SLP and total cloud amount (Yan et al., 1988; Chen et al., 1989). The overlaying of these two oscillations approaches to the actual SST curve quite well in the EEP. Generally, the QBO of the SST in the equator of the western Pacific (EWP) propagates eastward to the ECP, and in the EEP it moves westward. The QBO of the U spreads eastward from the Indian Ocean to the central Pacific. Besides, Chen Longxun and Chen Duo et al. (1989) discussed the propagation of the QBO of rainfall over

China and discovered two routes. One of them originates in the northeast of China, extends westward and southward and reaches the western part of north and the northwest of China; the other appears over the coast of the South China Sea, moves northward and westward and arrives at the lower, middle and upper reaches of the Yangtze River. It indicates that the interannual change of the weather in China is influenced by both the tropics and the polar region.

Since 1988, the COADS has been complemented and the COADS II from Jan.1980 to Dec.1987 is available. We combined the COADS I and the COADS II to obtain a data set from 1950 to 1987. Using this data set, we analyzed the propagation and the evolution of the QBO in the air-sea system and the characteristics of air-sea interaction.

II. DATA AND METHOD

Because of the small content of our computer, the COADS with $2^\circ \times 2^\circ$ grid system was simplified to be a data set with $4^\circ \times 4^\circ$ grid system. We consider that $4^\circ \times 4^\circ$ grid system can be well used to reveal the large scale features. In COADS, there are some points without records. Using the methods introduced by Yan et al. (1988) and Chen et al. (1989), we made the continuous time series of data and filtered out the QBO component from the anomalies of the SST, the U, V and the SLP, respectively. Then we investigated the QBO component with the method of the complex empirical orthogonal function (hereafter named CEOF). The method of the CEOF is as follows:

For the filtered anomaly series $R_j(t)$, where the subscript j is a spatial position index and t is time, using the Hilbert transformation, we have

$$\hat{R}_j(t) = \sum_{l=-\infty}^{\infty} R_j(t-l)h(l), \quad (1)$$

where

$$h(l) = \begin{cases} \frac{2}{\pi l} \sin^2\left(\frac{\pi l}{2}\right) & l \neq 0, \\ 0 & l = 0. \end{cases}$$

Then a new complex time series $\dot{R}_j(t) = R_j(t) + i\hat{R}_j(t)$ is formed, where $R_j(t)$ is the real part of $\dot{R}_j(t)$ and $\hat{R}_j(t)$ is the imaginary part. It is the $\dot{R}_j(t)$ which can reveal the features of the original time series at different time. Theoretically $l = \infty$ in (1) but the sum must be truncated in practice, and the values of l , 7-25, are suitable for the calculation. We set $l = 12$ here.

The covariance matrix of $U(u = v_{jk})$ is given by

$$U_{jk} = \frac{1}{T} \int_{-T/2}^{T/2} \dot{R}_j(t) \dot{R}_k^*(t) dt,$$

where T is the time domain defined by the time series. $\dot{R}_k^*(t)$ is the complex conjugate and U is a Hermite matrix.

The expansion of $\dot{R}_j(t)$ is expressed as

$$\dot{R}_j(t) = \sum_n A_n(t) B_n(j),$$

where the complex time-dependent principal component $A_n(t)$ is given by

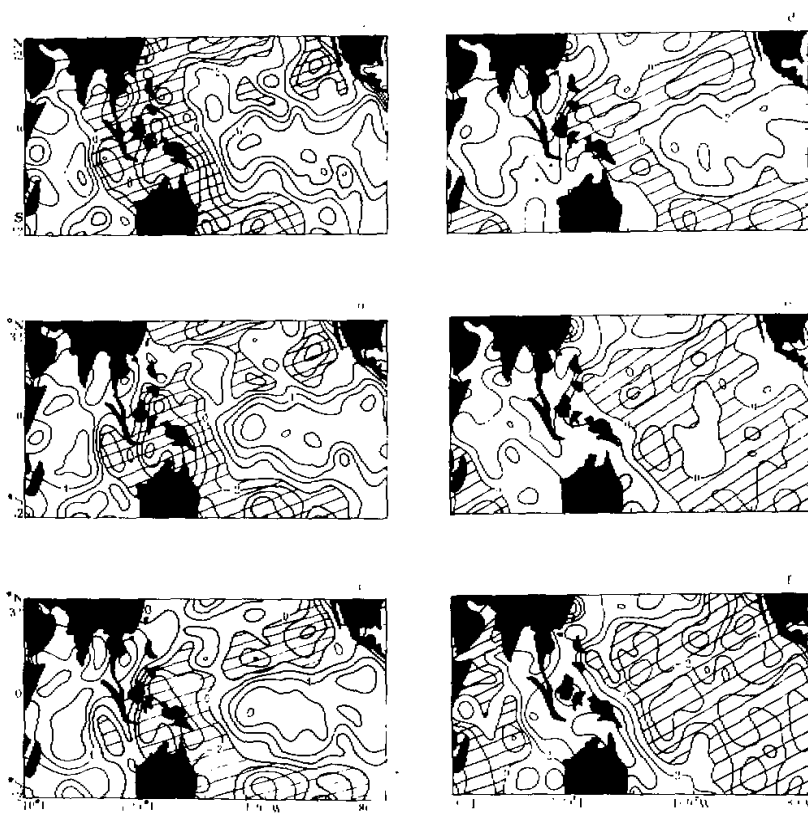


Fig.1. The composite phase field reconstructed from the corresponding field of the first eigenvector of SSTA's QBO. The negative regions are indicated by slant lines. Unit: 0.1°C . a) phase 0 (month 0). b) phase $\pi/6$ (month 2). c) phase $\pi/3$ (month 4). d) phase $\pi/2$ (month 6). e) phase $2\pi/3$ (month 8). f) phase $5\pi/6$ (month 10).

$$A_n(t) = \sum_j \hat{R}_j(t) B_n(j),$$

with proper normalization $\langle B_n B_m^* \rangle_j = \delta_{nm}$ and hence $\langle A_n A_m^* \rangle = \lambda_n \delta_{nm}$, where λ_n and $B_n(j)$ are the real eigenvalue and complex eigenvector of Hermite matrix U , respectively. $\delta_{nm} = 1$ for $n = m$; otherwise, $\delta_{nm} = 0$, and $\langle \rangle$ denotes the average of the series.

Thus, the contribution of the K th complex principal component to the total variance is given by $\lambda_k / \sum_{i=1}^K \lambda_i$. The K_{th} ($k = 1, 2, \dots, n$) eigenpattern has four measures: the spatial phase function $\theta_k(j)$, the spatial amplitude function $A_k(j)$, the temporal phase function $\theta_k(t)$ and the temporal amplitude function $A_k(t)$, they can be expressed as

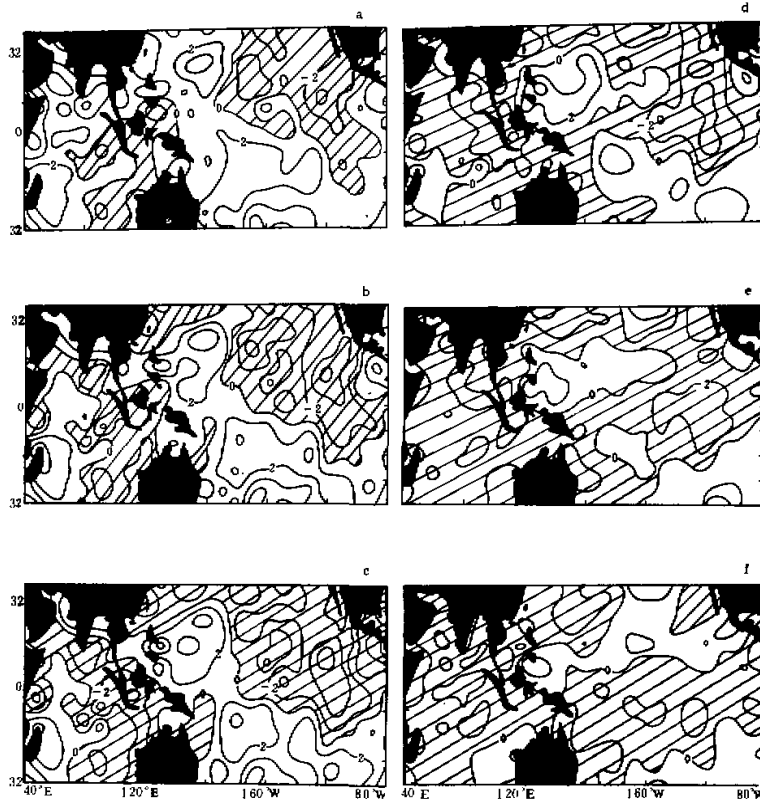


Fig.2. As in Fig.1, except for the second main component.

$$\theta_k(j) = \arctan[I_m B_k(j) / \text{Re} B_k(j)],$$

$$A_k(j) = [B_k(j) B_k^*(j)]^{1/2},$$

$$\theta_k(t) = \arctan[I_m A_n(t) / \text{Re} A_n(t)],$$

$$A_k(t) = [A_n(t) A_n^*(t)]^{1/2}.$$

We also constructed the fields corresponding to the first two eigenvectors and composed the fields of 12 phases corresponding to the temporal phases $0, \pi/6, \pi/3, \pi/2, 2\pi/3, 5\pi/6, \pi, 7\pi/6, 4\pi/3, 3\pi/2, 5\pi/3$ and $11\pi/6$, respectively.

III. ANALYSIS OF COMPOSITE FIELD FOR QBO OF SSTA

Fig.1 gives the composition of the reconstructed field corresponding to the first eigenvector of SSTA's QBO, which shows that the phases of $0, \pi/6, \pi/3, \pi/2, 2\pi/3$ and $5\pi/6$ correspond to the months 0, 2, 4, 6, 8 and 10, respectively. The process from warm water to cold water in the EEP is shown in Fig.1a-f. The fields of the phases $0-5\pi/6$ are

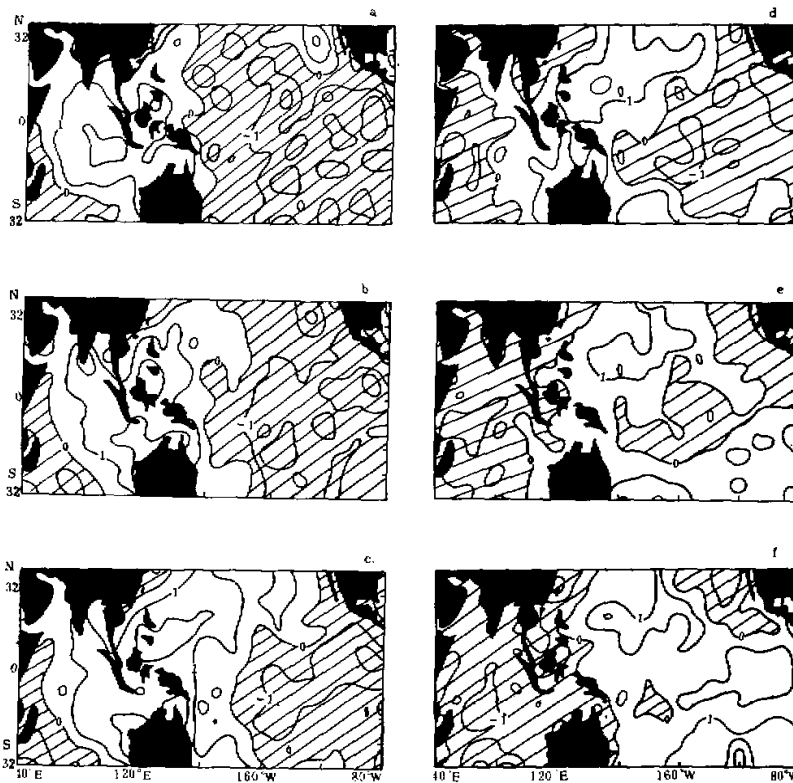


Fig.3. As in Fig.1, except for the SLP's QBO. Unit: 0.1 hPa.

identical to those of the phases $\pi-11\pi/6$ but with opposite signs, for simplicity, we only present the phases $0-5\pi/6$ here.

In the phase 0, it can be seen from the distribution of signs that (In the tropics, the eastern Pacific and the Indian Oceans are in warm water phase) and the area of the western Pacific is in cold water phase. This kind of pattern has been found for many years. It tells us that the distributions of SSTa in these oceans are highly correlative. It should be noted that there are two SSTa centers in the EEP. One of them is located in the central Pacific and the other is in the east part of the EEP, nearby the coast of South America. It also illustrates that during the occurrence of warm water in the eastern Pacific, the formation processes of these two warm water regions are different. The cold water regions are located in the areas of the South China Sea, the coast of Indonesia and the west part of the subtropics of the southern Pacific (SEP) to the east of Australia. The cold water centers are at $120^{\circ}\text{E}, 0^{\circ}\text{N}$; $130^{\circ}\text{E}, 10^{\circ}\text{S}$ and $160^{\circ}\text{W}, 30^{\circ}\text{S}$ respectively. Besides, there are still two cold water centers in the north part of the western Pacific (near 16°N).

In the phase $\pi/6$, the cold water region in the west part of the southern Pacific obviously extends eastward. At the phase $\pi/2$ (Fig.1d), it has stretched from 140°W to the coast of South America; then it extends northward at the phase $2\pi/3$ (Fig.1e). By the time of the

phase $5\pi/6$, a cold water center forms in the EEP. This cold water center (hereafter named E center of EEP) appears first in the eastern coast of Australia, and propagates counterclockwise in the subtropics. After arriving at the equator, it strengthens in intensity. The result is the same as that obtained by Yan et al. (1988) and Chen et al. (1989) using lag-correlation method. From Fig.1, we also notice that after the phase $\pi/6$, the water in the South China Sea has become warm water rapidly, and then the warm water spreads southward. In the phase $\pi/3$, two cold water centers in the eastern part of the subtropics of the northern Pacific (SNP) have combined together. Two months later, they connected with another cold water region in the EWP. Then the cold water center in the EWP moves eastward. By the time of the phase $5\pi/6$, it arrives at the ECP (hereafter named W center). Meanwhile, the warm water, which comes from South China Sea and moves southward, dominates the EWP and forms a warm water center there. At the same time, the water from southern Pacific to the east of Australia has also become warm water. Thus, the originations of cold water in the EEP have two processes. One originates from the west part of the SSP, propagates counterclockwise to the east part of the EEP to form the E center; the other first appears in the SNP, then moves counterclockwise to the EWP, and then extends eastward along the equator to the central Pacific to form the W center. Owing to the different originations, the influences on atmosphere are different.

Accounting for the total variance, the variance percentages of the first and the second main components are 23.28% and 13.62%, respectively. So, the sum of the percentages of these two main components is 36.90% of the total variance. Now we discuss the evolution of the second main component.

In Fig.2, at the phase 0, there is a negative anomaly region in the EEP, which is just located in the juncture of the two positive centers in Fig.1a. This means that in the composite field of the QBO, these two centers in Fig.1a will be more obvious. After the phase 0, the negative center enhances rapidly in the eastern Pacific. In the phase $\pi/3$, the negative region has dominated the whole EEP. But the center is still in 110°W and gradually weakens. By the time of the phase $5\pi/6$ (Fig.2f), the area near the equator (from 40°E to 100°W) is negative except for the part of the EWP region ($120^\circ\text{--}150^\circ\text{E}$). The distribution resembles that of the phase $5\pi/6$ in Fig.1, but the intensity is very weak. Besides, we can not find obvious movement of this oscillation. So the second main component is mainly a stationary wave oscillation modulating the first main component.

From Fig.1a–f and Fig.2a–f, we also find that the signs of the QBO of the SSTA change to the opposite one in the northern Pacific and the southern Pacific. For the first main component (Fig.1), as an example, at the phase 0, the distributions are the positive anomaly in the southeastern Pacific and the negative one in the southwestern Pacific. In the phase $5\pi/6$, the pattern of the SSTA is opposite to that of the phase 0. The change of the second main component is similar. It indicates that for the QBO, the variations of the SSTA in the Indian Ocean and the Pacific ocean are correlative.

IV. ANALYSIS OF COMPOSITE FIELD FOR QBO OF SLP

According to the date of each phase decided from the CEOF method for the SSTA's QBO component, we got six phase composite fields of the SLP. They are shown in Fig.3 (the first main component) and Fig.4 (the second main component) respectively.

Fig.3a shows that within the region of 32°S – 32°N and 40°E – 100°W , the positive anomaly is basically located in the west of 160°E and the negative one is in the east of it. This means that the warm water region in the eastern Pacific corresponds to the negative anomaly

of the SLP and the western Pacific and the Indian Ocean are in the area of the positive anomaly of the SLP. After the phase 0, the areas of the positive and the negative anomalies almost entirely move eastward. At the phase $5\pi/6$ (Fig.3f), the distribution is contrary to that of the phase 0; the Western Hemisphere is positive anomaly and the Eastern Hemisphere is negative one. This characteristic coincides with the results of three and a half year oscillation achieved by Yasunari (1987) and Krishnamurti (1986). It should be noticed that for the second main component, the evolutionary feature of the SLP anomaly is also in agreement with that of the SSTA. In other words, during the period from the phase $\pi/3$ to the phase $2\pi/3$, the positive anomaly of the SLP near the EEP couples with the negative anomaly of the SST in that area; and it is different from the feature of the first main component that there is no obvious eastward or westward movement. The oscillation of the second main component of the SLP is of a kind of stationary wave.

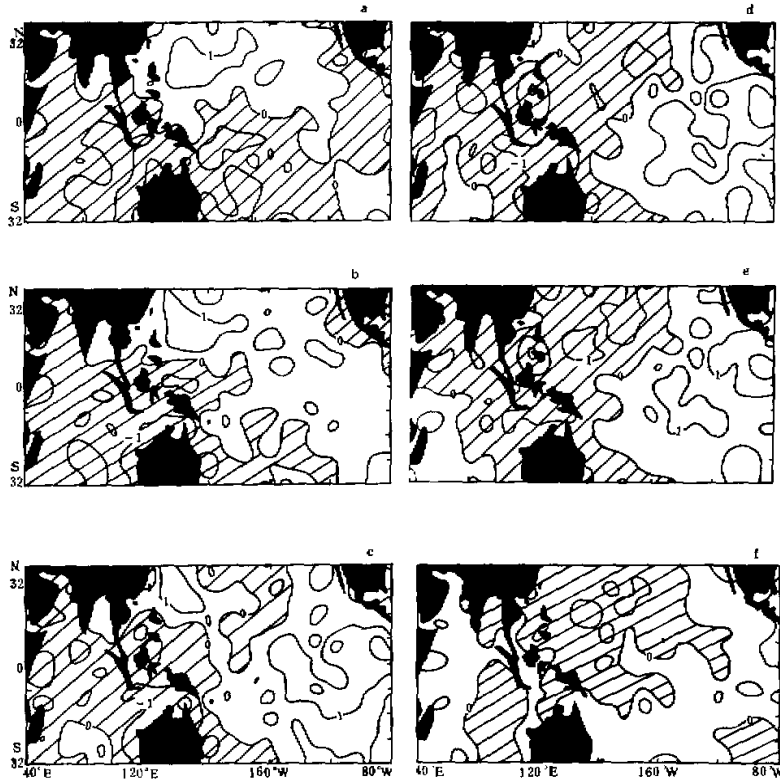


Fig.4. As in Fig.2, except for the SLP's QBO. Unit: 0.1 hPa.

V. ANALYSIS OF COMPOSITE FIELD FOR QBO OF ANOMALY STREAMLINE FIELD

The composite field of the QBO's anomaly streamline field for the first main component is shown in Fig.5. In the first phase, the SSTA of the EEP is in warm water phase and the Indian Ocean is a convergence region with east wind anomaly. The EWP is of west wind anomaly expanding to 160°W where a strong convergence area overlapping the warm water center of the central Pacific at the phase 0 in Fig.1. Besides, In the west part of warm water center which is in the east part of the EEP exists another convergence area. It is also noted that the east wind anomaly in the equator of the Indian Ocean links with the anomaly anticyclone in the tropics, and the west wind anomaly in the EWP connects with the anomaly convergence zone and the cyclonic anomaly streamline field in the tropics of the Northern and the Southern Hemispheres. As the case of the Indian Ocean, the east wind anomaly of warm water phase in EEP also links with the anomaly anticyclonic circulation in both Hemispheres. Therefore, in the phase 0, the equatorial circulation of SSTA's QBO component reflects the same phase anomaly circulations in the Northern and the Southern Hemispheres.

By the time of the phase $\pi/6$, an anomaly anticyclone appears in the tropics of East Asia, namely in $120\text{--}130^{\circ}\text{E}$ and $5\text{--}15^{\circ}\text{N}$; and at the same longitude in the Southern Hemisphere, the circulation of anomaly anticyclone already exists at the phase 0. In the phase $\pi/3$, the circulations of the northern and the southern anomaly anticyclones in East Asia develop and lead to west wind anomaly appearing in the west part of the EWP and in the equator of the western Indian Ocean. From the phase $\pi/2$ to the phase $2\pi/3$, the east wind anomaly in the EWP extends eastward to the ECP as the northern and the southern anomaly anticyclones move eastward. A divergence region forms at the phase $5\pi/6$ in the equator of 160°W , namely the east side of the east wind anomaly. This area is in the same location with the negative center of the SSTA in the ECP at the phase $5\pi/6$ in Fig.1.

It is necessary to point out that with the eastward movement of anomaly anticyclone in East Asia mentioned above, East Asia lies in the western side of the anomaly anticyclone as the beginning of phase $\pi/2$. That is to say that the SSE wind in East Asia was strengthened in first six months of cold water prevailing period (for the QBO) in the EEP. So, it can be predicted that the NNW wind anomaly will prevail in East Asia six months earlier than the prevailing period of warm water in the EEP. This has been verified at the phase 0 (Fig.5a). Coordinating with the change of circulation in the Northern Hemisphere, the anomaly anticyclone appears in the SSP, where is just the cold water center (Fig.1) at the phase $\pi/6$. Afterwards, there are eastward movements of anomaly anticyclone circulation, the east wind anomaly and the cold water region. In the phase $\pi/2$, a divergence center appears at 20°S , 120°W . The center still stays there at the phase $5\pi/6$. This may be the reason of the maintenance of cold water center in the eastern part of the eastern Pacific. Therefore, the process is different from that of another divergence center corresponding to the cold water center of the ECP.

For illustrating the variation of the strong wind region in the process mentioned above, we made the distribution of scalar speed $\bar{V}(\bar{V} = \sqrt{u^2 + v^2}$, u and v are the zonal and the meridional wind components, respectively), see Fig.6.

In the phase 0 (Fig.6a), there are three strong anomaly wind areas in the equator—two strong east wind areas in the Indian Ocean and the eastern Pacific and a strong west wind area in the western Pacific (all the wind is anomalous). After the phase 0, each strong wind area slowly moves eastward and enhances. At the phase $\pi/3$, there is a sudden change—the

anomaly center of strong east wind in the equator of the Indian Ocean reduces suddenly. By the time of the phase $\pi/2$, a weak east wind anomaly area appears in the EWP. It develops into an anomaly center of strong east wind in the central Pacific at the phase $5\pi/6$. In the process of east moving of the anomaly anticyclone in the tropics of the Northern Hemisphere in the phase $\pi/2$ the velocity rapidly enhances at the phases $2\pi/3$ and the phase $5\pi/6$. The convergence and the divergence areas form in the EWP and the central Pacific, respectively. There is no sign to indicate that the variation of wind strength in the EEP is influenced by the eastward propagating wind field in the Indian Ocean. It may be caused by the variation of the circulation in the western Pacific.

VI. DISCUSSIONS

It can be confirmed that the air-sea coupled QBO truly exists in ocean and atmosphere. The characteristics are:

(1) For the first CEOF main component of QBO, in both periods of warm water and cold water in the EEP, each of the SSTs in the ECP and the eastern part of the EEP has its anomaly center. The former originates from the SNP, propagates westward to the western Pacific, then turns southward to the equator and goes eastward to the central Pacific. The latter appears in the SSP, moves eastward, and then northward to the equator and reaches the east part of the eastern Pacific. The QBO of the SSTA for the second CEOF main component is of a stationary wave oscillation.

(2) Corresponding to the first process of the SSTA, the oscillation of the SLP moves entirely eastward in both Hemispheres. When the EEP is in warm water phase, the positive anomaly of the SLP is in the Eastern Hemisphere and the negative anomaly is in the Western Hemisphere, and vice versa. The change of the SLP, occurring in the phase $2\pi/3$ and the phase $5\pi/6$, is rather quick accompanying the transform of warm water to cold water.

(3) In the warm water period, there are two convergence centers corresponding to two warm water centers, respectively. These two centers have different circulation processes. For the center in the ECP, the process of the circulation first occurs in the tropics in East Asia, mainly in the Northern Hemisphere. The process is that the tropical anticyclone extends southward to the equator and the east wind anomaly in south side of the equator also spreads to the equator so as to replace the west wind anomaly in the warm water phase. Afterwards, this anticyclone moves eastward; following it, the equatorial east wind anomaly extends eastward too; finally, a strong divergence center forms in the ECP. The strong east wind anomaly in the equator of the Pacific does not come from the Indian Ocean, it originates locally, then propagates eastward and strengthens rapidly. The results also demonstrate that it takes 4–6 months for the signal of the SST travelling from the western Pacific to the central Pacific, and that the strong wind lasts about 2–4 months. As to the SSTA center in the east part of the eastern Pacific, it has a close relation to the propagation of the SSTA center in the Southern Hemisphere and its correspondent circulation.

It is necessary to point out that different phases of the SSTA's QBO have different circulations in the region of 32°N – 32°S . In the warm water phase in the EEP, the anomaly anticyclone circulation dominates the east side of 0° – 32°N area in the Pacific Ocean, and the anomaly cyclone circulation in the west side. Therefore, the area of 0° – 32°N in East Asia is of the north wind anomaly. In contrary, the south wind anomaly prevails there when cold water is in the EEP. Despite of the complexity of the circulation in the Southern Hemisphere, it is basically in agreement with that in the tropics of the Northern Hemisphere. So the region of East Asia in the Southern Hemisphere is of the SSE wind anomaly in warm water phase and

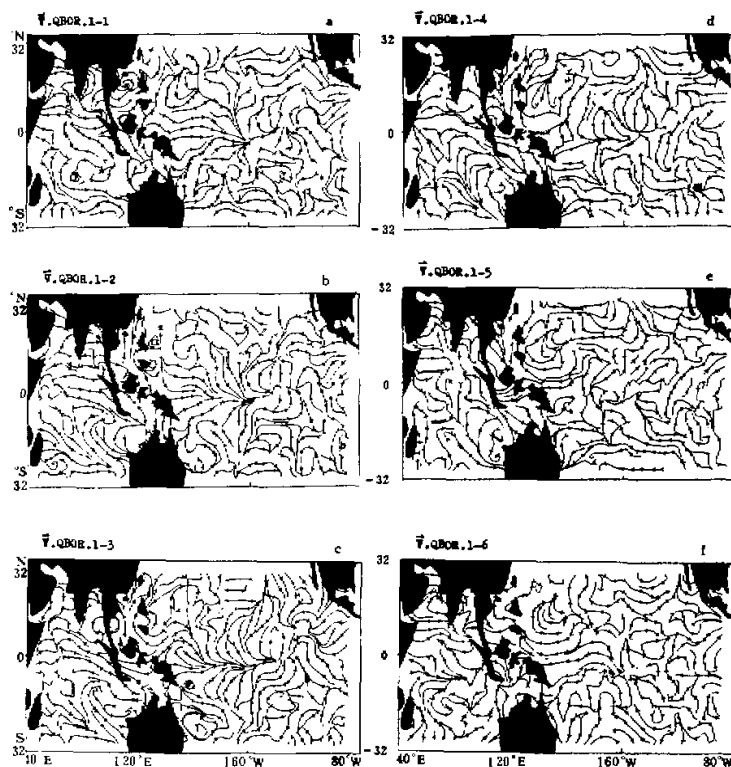


Fig.5. As in Fig.1, except for QBO of streamline field.

of the NNW wind anomaly in cold water phase. Since the variation of the circulation is earlier than that of the SST in the EEP, and it is also influenced by the air-land system, the QBO is actually a coupled process of air-land-sea system.

It needs to be emphasized that there are two warm or cold centers of the SSTA in the EEP for the QBO. The SSTA center in the ECP is mainly influenced by the circulation in the Northern Hemisphere; meanwhile it is also affected by the EWP. The SSTA center in the east part of the eastern Pacific, originating in the subtropical southwestern Pacific area being located to the east of Australia, is principally affected by the Southern Hemisphere. Because of the different formation processes of two SSTA centers, they have different features of the warm water or cold water. This may be helpful for us to understand the mechanism of the El Nino. The circulation in East Asia plays an important role in the early period of the formation of warm or cold water in the ECP, and the circulation in the southwestern Pacific is emphasized for the formation of warm or cold water in the east part of the eastern Pacific. Similarly, the circulation of East Asia may be affected even more by the cold or warm water center in the ECP. But a lot of work should be done to verify it.

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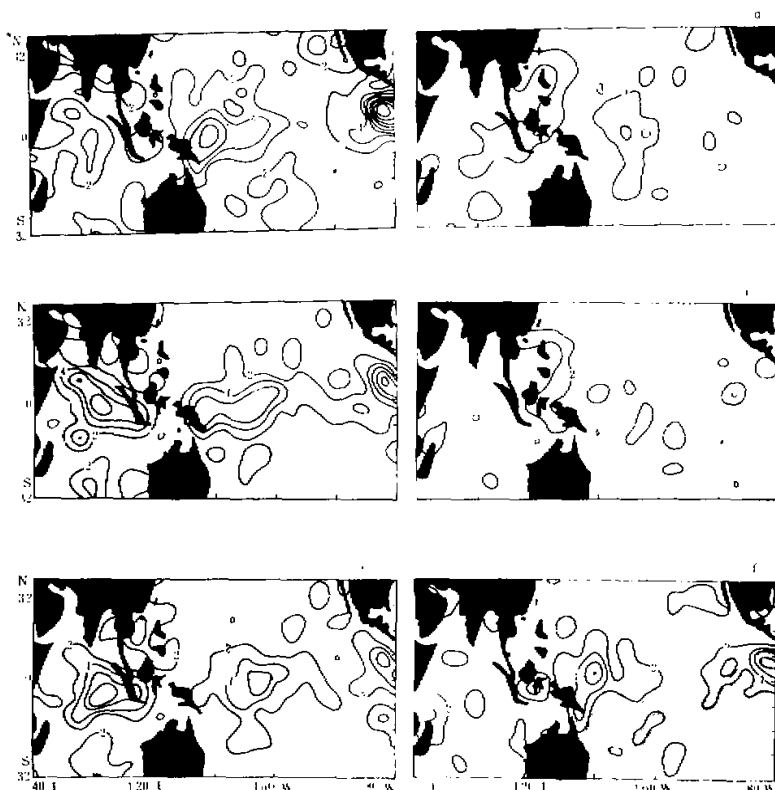


Fig.6. As in Fig.1, except for scalar speed \bar{V} . Unit: 0.01 m / s.

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